(12) UK Patent Application (19) GB (11) 2 300 341 (13) A

(43) Date of A Publication 30.10.1996

(21) Application No 9502804.9

(22) Date of Filing 14.02.1995

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(51) INT CL[6]
H05G 2/00

(52) UK CL (Edition O)
H5R REL

(56) Documents Cited
EP 0105032 A2 US 5247562 A

(58) Field of Search
UK CL (Edition O) H5R REL REU
INT CL[6] H01S 3/00 4/00 , H05G 2/00
Online: EDOC,JAPIO,WPI

(54) X-ray source using electron beam and laser cavity

(57) An electron beam 10 is introduced into a laser cavity defined by totally reflecting mirrors 7,8 and guided by bending magnets 1,2 and focussing lenses 12-15. The electrons interact with the beam generated by laser 9, which may be internal or external, to produce an X-ray beam 17 by inverse Compton scattering. The direction of the X-ray beam can be controlled by steering the electron beam. Different mirror and window arrangements are disclosed. Polarisation of the X-radiation can be controlled by controlling the laser beam. A single electron source can feed a series of laser cavities to produce multiple X-ray beams.

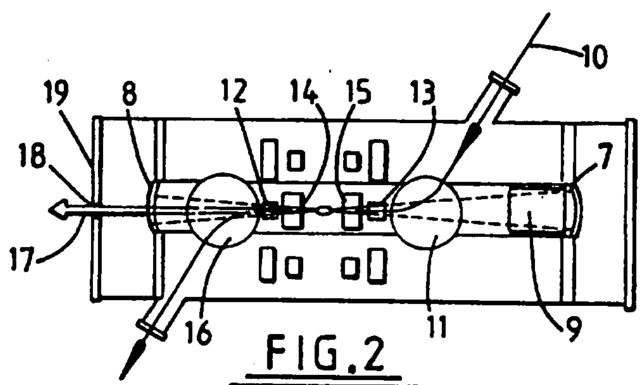

FIG.2

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At least one drawing originally filed was informal and the print reproduced here is taken from a later filed formal copy.

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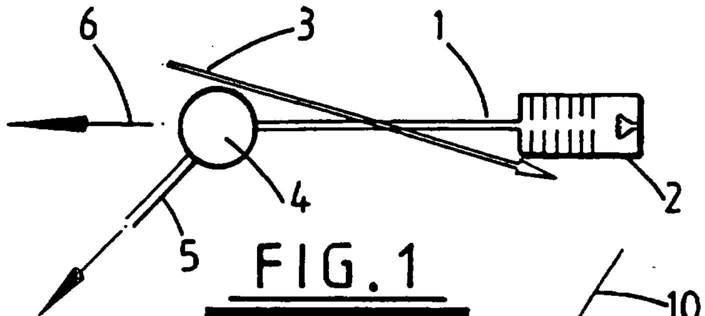

FIG.1

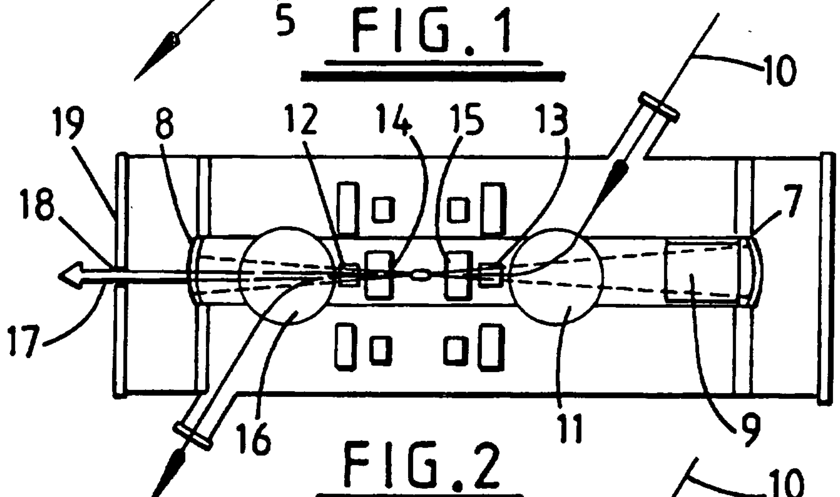

FIG.2

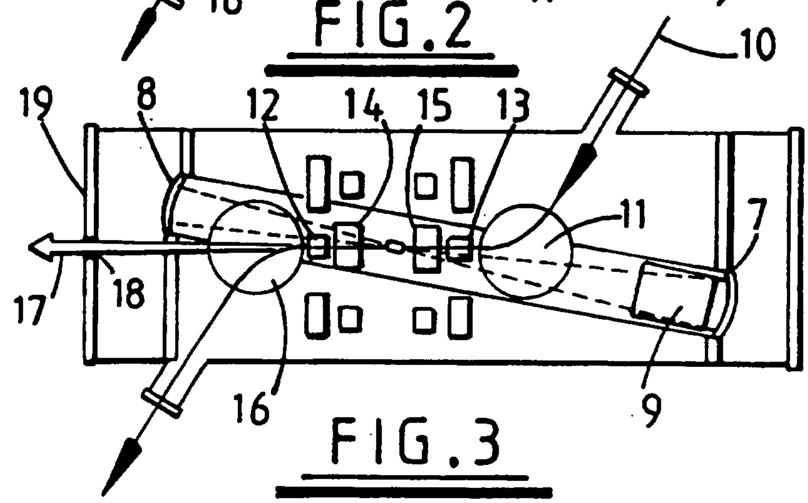

FIG.3

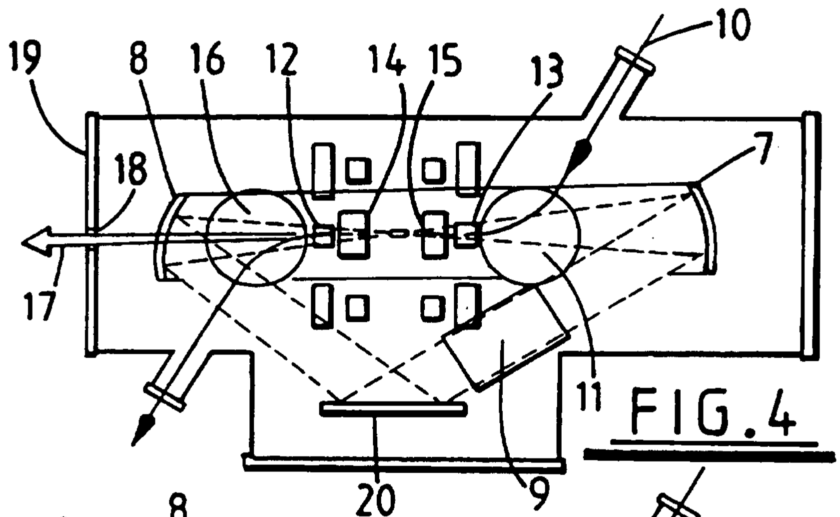

FIG.4

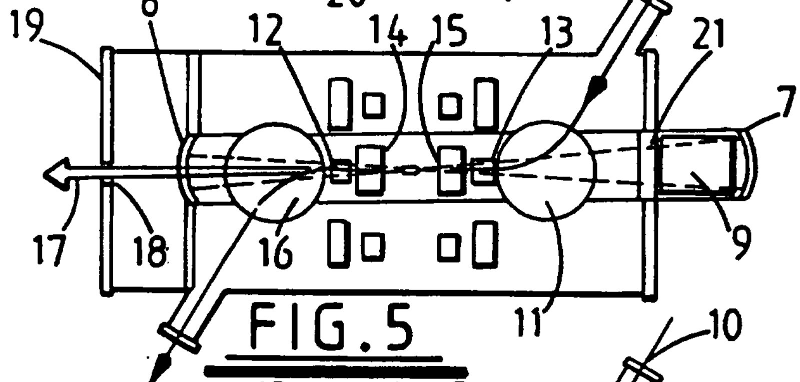

FIG.5

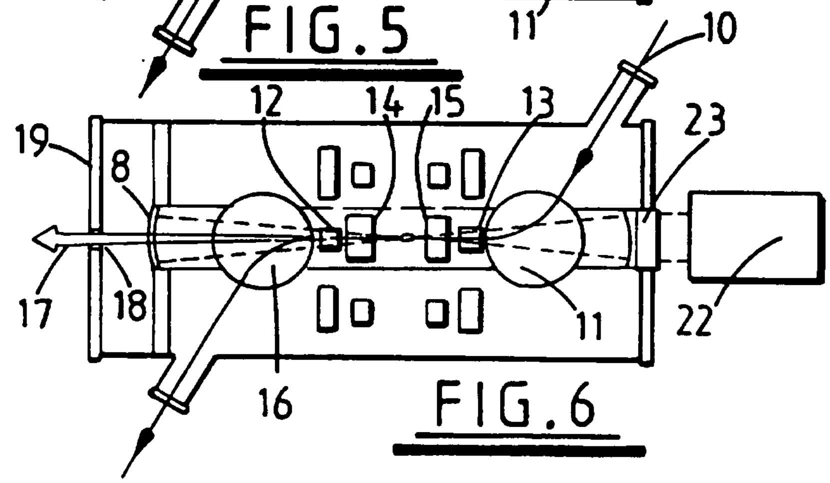

FIG.6

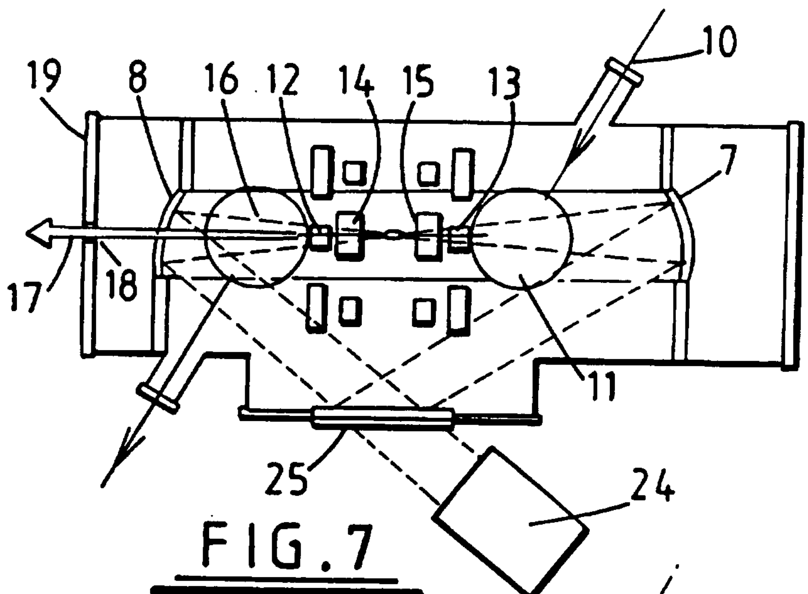
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FIG.7

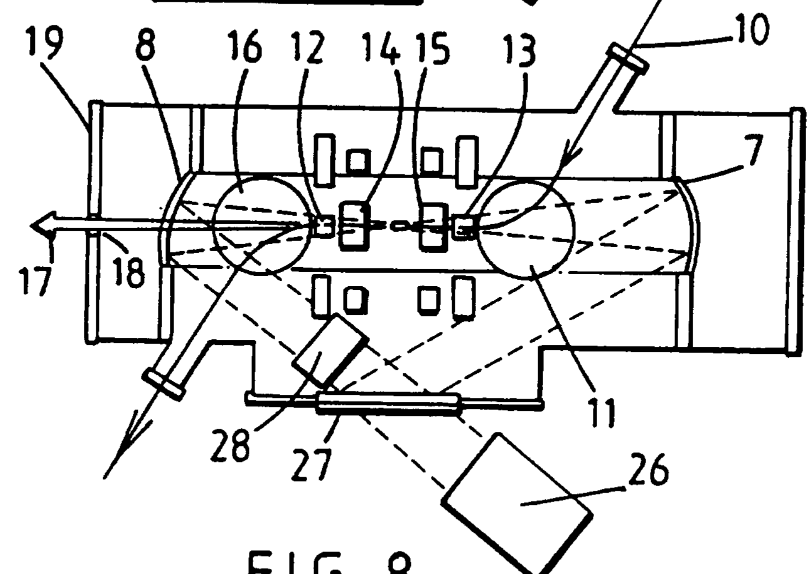
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FIG.8

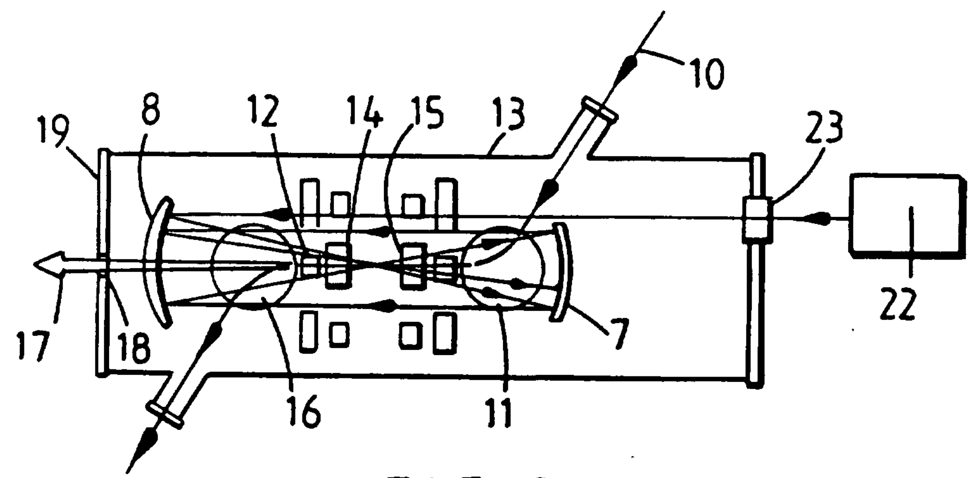

FIG.9

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X-RAY SOURCE

The present invention relates to an x-ray source, and in particular to an x-ray source relying upon inverse Compton scattering.

It is conventional practice to generate x-rays for use in laboratory investigations by using fluorescent or Bremsstrahlung sources. The performance of such sources is, however, inadequate for many applications, and in particular such sources cannot produce x-rays of high brightness. It would be highly desirable to provide an x-ray source capable of producing a performance equivalent to that of synchrotron sources without the high costs associated with such sources.

The inelastic scattering or inverse Compton interaction has already been exploited by the nuclear physics community to generate gamma rays in the 100 - 1000 MeV range for photonuclear absorption studies where there is no available alternative gamma ray source. For example, the documents M. Preger, B. Spatero, R. Bernabel, MP. De Pascale and C. Schaerf, Nucl. Instr. Methods A249, 299, 1986; C.E. Thorn, G. Giordano, O.C. Kistner, G. Matone, A.M. Sandorfi, C. Schaerf and C.S. Whisnant, Nucl Instr. Methods A285, 447, 1989; W.D. Andrews, F.E. Carroll, J.W. Waters, C.A. Brau, R.R. Price, D.R. Pickens, P.A. Tompkins & C.F. Roos, Nucl. Instr. Methods A318, 189, 1992; ESRF Foundation Phase Report, ESRF at Grenoble, France describe activities related to the generation of high energy gamma rays for nuclear photodisintegration studies using a GeV synchrotron storage ring as an electron source. The system described in the above publication of Andrews et al uses a 45 MeV free electron laser with self-scattering to produce an x-ray beam for in-house medical research. In all of the described systems output photon fluxes are low.

U.S. Patent No. 5227733 describes an apparatus which can be used to generate x-rays which relies upon inverse Compton scattering. In the described apparatus, relativistic electrons are stored in a closed loop and a light beam is caused by an array of reflectors to follow the same path as the electrons. The radiation produced is, however, of low intensity and predominantly in the UV region of the electromagnetic spectrum. The source has no unique source position and emits isotropic soft x-rays with energies of less than 10 keV.

It is an object of the present invention to provide an improved x-ray source.

According to the present invention, there is provided an x-ray source comprising a laser cavity, and means for introducing a relativistic electron beam into the cavity such that the beam and laser radiation within the cavity interact to generate x-rays.

A high density photon field may be generated within the cavity and the electron beam may be focused and steered by applied magnetic fields to achieve a high interaction probability between the high density photon field and the electron beam.

The cavity may be in the form of a resonator or a multiply reflecting cell.

Embodiments of the present invention will now be described, by way of example, with reference to the accompanying drawings, in which:-

Fig. 1 schematically illustrates a conventional laser-electron interaction configuration;

Figs. 2 to 9 schematically illustrate seven different embodiments of the present invention.

Referring to Fig. 1, an electron beam 1 generated by a LINAC 2 interacts with a laser beam 3. The electron beam is deflected by a magnetic field perpendicular to the plane of the drawing represented by the circle 4, the diverted beam 5 being delivered to an electron absorption device (not shown).

X-rays are generated as a result of the interaction of the electron beam 1 and the laser beam 3. Such x-rays are unaffected by the magnetic field 4 and are emitted in the direction represented by arrow 6.

The cross section for colliding electron and photon beams is given in "The Theory of Photons and Electrons" by JM Jauch and F Rohrlich, Springer, 1976. It can be shown that the differential cross section of the output x-ray beam falls rapidly with deviation of the direction of the scattered photons away from the electron momentum direction. Accordingly in the configuration illustrated in Fig. 1, which is that adopted for most of the known research facilities installed in the academic laboratories referred to in the above documents, it is known that the electron and laser beams should be as collinear as

possible.

In addition to the desirability of having collinear laser and electron beams, it is also desirable to provide a high density photon field to maximise interactions. This can be accomplished by a "brute force" method in which very high power laser sources are used in the known systems, preferably in pulse mode, such that a laser pulse interacts with a synchronised electron pulse. Unfortunately the provision of high powered laser sources in itself adds to the cost of the apparatus.

Referring to Fig. 2, the illustrated apparatus overcomes the problems referred to with reference to Fig. 1 by trapping a laser beam within a resonant cavity through which the electron beam is directed. In the arrangement of Fig. 2, a laser cavity is defined between totally reflecting end mirrors 7 and 8 which are provided in the end walls of a vacuum enclosure. A laser beam is generated between the mirrors 7 and 8 by conventional equipment including lasing material, optical pumping and frequency selection elements represented by block 9. An electron beam 10 is introduced into the enclosure so as to enter a magnetic field generated by a first bending magnet 11. The magnet 11 deflects the electron beam onto the laser axis defined between the mirrors 7 and 8. The diverted electron beam is focused by magnetic lenses 12 to 15 and deflected by a magnetic field generated by a second bending magnet 16 away from the cavity axis, the deflected beam being delivered to a beam dump (not shown). The magnetic lenses 12 to 15 may be conventional quadrupole devices and the bending magnets 11 and 16 may be conventional dipole magnets.

As the laser beam is trapped within a resonator the photon field density will be several orders of magnitude greater than that readily available from external laser beam sources. The electron beam may be accurately steered and focused so as to be collinear with the high field density laser beam so as to ensure maximum interaction probability. As a result a high intensity x-ray beam 17 is generated which exits the enclosure through mirror 8 and a window 18 in an end flange 19.

Wavelength selective elements may be provided within the vacuum enclosure. Accordingly either a monochromatic, polychromatic or wide band x-ray output may be generated. The output energy is

tunable, for example from one keV to one MeV. Linear or circular polarisation may be selected. DC or pulsed operation at frequencies typically greater than 1 kHz are readily achievable. Thus the device is of small size and cost and yet produces a high brilliance output of the type required to generate geometrical sharpness in, for example, radiographic images. The device is therefore appropriate for many applications, including independent use in small laboratories. Furthermore, a single apparatus may deliver x-ray outputs to a multiplicity of users.

Figs. 3 to 8 illustrate alternative embodiments of the present invention to that shown in Fig. 2. Where appropriate, the reference numerals used in Fig. 2 are also used in Figs. 3 to 8 for the equivalent components.

The embodiment of Fig. 3 corresponds to that of Fig. 2 except for the fact that the laser axis is offset somewhat relative to the electron beam axis within the cavity so that the X-ray output does not pass through the end mirror 8. With the arrangement of Fig. 3, although the optimum arrangement of having the electron and laser beams co-linear is not achieved, the angle of inclination between the two beams is relatively small and in some applications this may be acceptable given that in such applications it is desirable to have the x-ray beam passing from the cavity without passing through a main laser cavity and mirror.

Referring to Fig. 4, the illustrated embodiment corresponds to that of Fig. 2 except for the fact that an additional mirror 20 is provided, the mirrors 7 and 8 are inclined so as to define a ring path for the laser beam, and the laser beam generating equipment 9 is located between the mirrors 7 and 20.

Referring to Fig. 5, the illustrated embodiment corresponds to that of Fig. 2 except for the fact that the laser elements 9 and the end mirror 7 are located external to the vacuum enclosure of the electron beam. The laser is coupled into a resonant passive cavity through an optical window 21 provided in the wall of the vacuum enclosure.

Referring to Fig. 6, in the illustrated embodiment the laser beam is generated by a free standing laser 22 which is external to the vacuum enclosure. The output of the free standing laser is coupled

into the resonant passive cavity through a matched coupler and partially transmitting end mirror 23.

Referring to Fig. 7, in the illustrated embodiment once again an external free-standing laser 24 generates the laser beam and that laser beam is coupled into a ring-resonator through a mirror 25. Thus the arrangement is similar to that of Fig. 4 except for the fact that the laser beam is generated by a free-standing laser external to the vacuum enclosure.

Referring to Fig. 8, in the illustrated arrangement a free-standing external laser 26 is used to pump a non-linear optical element so as to generate radiation tuned to an internal optical cavity operating at a frequency different from that of the pump laser. An optical element 27 which is fully transmitting to the external pump radiation but fully reflecting to the radiation generated within the optical cavity couples the output of the external laser 27 to the cavity. A non-linear optical element 28 acts as either a second harmonic generator or an optical parametric oscillator.

Referring to Fig. 9, the illustrated embodiment correspnods to Fig. 6, but the external free standing laser 22 generates a beam which enters through window 23 and is multiply reflected inside the non-resonant cavity formed by mirrors 7 and 8.

The use of an external laser source as illustrated in some of the above embodiments has the advantage of allowing for easy substitution of different sources so as to achieve different operating conditions.

Thus the present invention provides a compact and economic apparatus for achieving the inelastic scattering of laser light by relativistic electron beams such as are produced by widely available radiotherapy linear electron accelerators. Photon fluxes are achievable which are equivalent to what can be achieved from a 1 MCi radioisotope and stronger by several orders of magnitude than a high power rotating anode.

The apparatus of the invention would have a lower brightness than third generation synchrotrons but will offer permanent home laboratory access which for many applications will more than compensate for lower brightness. The output may be monochromatic (0.1% b.w.) or wide band (50% b.w.) and often no monochromator or even beam filter will be needed. The energy range can, furthermore, be

more readily extended to low and high values than in the case with synchrotrons.

In the apparatus of the invention, the directional output of the x-ray beam is selectable by steering the electron beam within the interaction cavity. This gives the possibility of very rapid scanning of the x-ray beam with no moving mechanical parts. This has not been possible hitherto.

Pulsed or rapid power level control may be achieved by control of a relatively low energy laser. Furthermore, polarisation of the x-ray beam can be controlled, again by control of a low energy laser beam. Of real economic significance is the fact that the laser-electron interaction cavity can be constructed as a bolt-on accessory to, for example, existing medical LINACs.

Each apparatus in accordance with the invention could be associated with its own electron source but it would be more efficient to use one electron source to feed a series of laser cavities to allow virtually independent multi-user operation. It is conceivable that one electron source could supply as many as 100 x-ray sources in accordance with the invention. Thus, in contrast to conventional sources which are essentially single user as there is only one source point, the apparatus of the invention can be extended indefinitely with, for all practice purposes, independent operation of each source.

In order to achieve photon output in the x-ray region, the electron beam may be supplied by a standard medical LINAC. The beam can be fed directly into the interaction laser cavity and then dumped. This is the arrangement illustrated in Figs. 2 and 3. There is, however, a more efficient way to use the electron beam. Given the relatively low energy of the electrons (less than 50 MeV) it is easy to trap them magnetically and they can, therefore, be stored in a magnetic loop as in a conventional storage ring, or they can be "bottled" in a totally reflecting structure. Synchrotron radiation losses from these electrons are very low with wavelengths in the infrared region and can be easily replaced by low power RF cavities. A pulse peak electron current from a LINAC of about 1A would then be increased by a factor of up to 100 in dependence upon the dimensions of the magnetic trap. Very high DC (not pulsed) currents are then possible for a very low average power consumption by the

LINAC. The time structure of the output radiation for a stored electron beam would be largely independent of the LINAC operating cycle.

Switching the delivered electrons from a LINAC to a series of magnetic traps would be useful in a system intended to allow independent operation of a series of sources. Such an arrangement would be a radiation-safe mode of operation since when the current in any particular magnetic trap has reached a required level the trap can thereafter be by-passed and ultimately the LINAC can be switched off.

As many hospitals already operate LINAC systems, the present invention could be widely applied in medical fields. Tunability, steerability and precise control of output power make them far more sensitive than existing medical apparatus and offer the prospect of better diagnostic and therapeutic radiation procedures. Tunability to the absorption edges of intravenous contrast enhancing agents enables a reduction in radiation dose levels of synchrotron-based imaging systems and devices in accordance with the invention will make this possible on a wide basis.

Industrial radiography requires highly penetrating gamma rays which are available usually only from radioisotopes of MCi activity. In some applications the Bremsstrahlung radiation from accelerated electron interactions with Tungsten targets is used. Both of these techniques have disadvantages. The radioisotope method is potentially hazardous and shielding must be provided which blocks most of the emitted radiation. Intensities from Bremsstrahlung sources can be high and the source is relatively safe but the measurements are necessarily less precise since a complicated radiation spectrum is generated which cannot be readily altered. In contrast, a source in accordance with the invention would produce a highly collimated beam (thus relatively safe) of equivalent intensity while the spectral properties can be finely controlled and adjusted for different radiographical inspection tasks. Chemical analysis can be enhanced both by tuning to absorption edges of impurity constituents of for example castings and by successive transmission measurements over a range of energies. Transportable embodiments of the present invention should be a practical possibility.

CLAIMS

1. An x-ray source comprising a laser cavity, and means for introducing a relativistic electron beam into the cavity such that the beam and laser radiation within the cavity interact to generate x-rays.

2. An x-ray source according to claim 1, comprising means for steering the electron beam by controlling magnetic fields within the cavity to control the direction of the output x-radiation.

3. An x-ray source according to claim 1 or 2, comprising means for controlling the laser radiation to control the polarisation of the output x-radiation.

4. An x-ray source according to any preceding claim, comprising a totally reflecting cavity within which the laser radiation is generated.

5. An x-ray source according to any one of claims 1 to 3, comprising an external laser source coupled to the cavity.

6. An x-ray source substantially as hereinbefore described with reference to any one of Figs. 2 to 9 of the accompanying drawings.

Application No:	GB 9502804.9	**Examiner:**	David Brunt
Claims searched:	1-6	**Date of search:**	17 April 1996

Patents Act 1977
Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.O): H5R (REL, REU)

Int Cl (Ed.6): H01S (3/00, 4/00), H05G (2/00)

Other: Online: EDOC, JAPIO, WPI

Documents considered to be relevant:

Category	Identity of document and relevant passage		Relevant to claims
X	EP 0105032 A2	(IMAGING SCIENCES) see Figures 2-4, page 10 line 13 to page 12 line 15, page 17 lines 5-19, and page 21 line 34 to page 22 line 11	1-4
X	US 5247562	(STEINBACH) see Figure 1 and column 5 line 11 to column 8 line 13	1,5

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
&	Member of the same patent family	E	Patent document published on or after, but with priority date earlier than, the filing date of this application.